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A new quantum effect in mesoscopic systems

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abstract

We have considered an open system consisting of a metallic ring coupled to two electron reservoirs. We show that in the presence of a transport current, circulating current can flow in such a ring even in the absence of magnetic field. This is purely a quantum effect and is related to the current magnification property of the ring near the resonant states. We find that the presence of impurity can dramatically enhance the current magnification effect at particular values of Fermi energies, whereas it can decrease the current magnification at some other values of Fermi energies. This is in contrast to the effect of the presence of impurity on persistent currents in closed isolated metallic rings in the presence of magnetic field, where persistent currents are always suppressed.

Key Words : Current magnification, open systems, mesoscopic systems.

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In the past decade physics of mesoscopic systems has emerged as an important area of research from basic physics and technology point of view. Mesoscopic physics deals with the metallic or semi-conducting material structures of nanometer scale[1]. The length scale associated with the sample dimensions in these systems are much smaller than the inelastic mean free path or phase breaking length of electrons. Thus the electronic motion becomes phase coherent over the entire sample. However, the motion of electrons can be ballistic, quasi-ballistic or diffusive. These sub-micron systems have now provided us with an opportunity for exploring quantum effects beyond the atomic realm. Some of the experimentally explored structures include high mobility metallic wires, zero dimensional electron systems or quantum dots, point contacts, rings, etc. They have revealed several interesting quantum mechanical properties at low temperatures, where interference of electronic waves, quantization of energy levels and discreteness of charge play major role. The experimentally observed phenomena related to transport properties are normal state Aharonov-Bohm oscillations in the resistance of a metallic loop pierced by a magnetic field, non-local relation among current and voltage, breakdown of local Onsager reciprocity relations, quantization of conductance in the point contact, Coulomb blockade effect in the micro-tunnel junctions, quenching of Hall effect in the narrow cross junctions, resonant tunneling phenomenon, quantum shot noise, to name but a few[1].

In recent years phenomenon of persistent currents (thermodynamic equilibrium currents) in mesoscopic rings in the presence of magnetic field, has attracted much attention from theoretical as well as experimental viewpoint[1-4]. This quantum phenomenon was first predicted theoretically by Büttiker et al[2]. The magnetic field destroys the time reversal symmetry and as a consequence, persistent current flow in the loop and is periodic in magnetic flux, with a period ϕ_0, $\phi_0 = hc/e$ being the elementary flux quantum. We show that circulating currents are possible in mesoscopic rings even in the absence of magnetic field. However, it requires the presence of a transport current across the system (open system). This is purely a quantum effect and is related to a current magnification property of the ring around the resonant states[5,6].

To this end we consider a one dimensional loop connected to two electron reservoirs by leads as shown in fig. 1. At the center of the upper arm there is a delta function potential scatterer at the site marked as X in the figure. The chemical potential of the left reservoir is μ_1 and that of the right reservoir is μ_2. The length of the upper arm is l_1+l_2 and that of the lower arm is l_3 and thus the circumference of the ring is $L = l_1+l_2+l_3$. We are considering the simple case when $l_1 = l_2$. If $\mu_1 > \mu_2$ then a transport current flows from the left reservoir to the right and in the opposite direction if $\mu_2 > \mu_1$. In the first case we consider the strength of the delta function potential V_0=0 and the transport current flows from left to right. The current injected[3-6] by the left reservoir into the left lead around the small energy interval dE is given by $dI_{in} = \frac{dn}{dE} f(E)dE$ where $v = \hbar k/m$ is the velocity of the carriers at the energy E, $\frac{dn}{dE} = \frac{1}{2\pi\hbar v}$ is the density of states in the perfect wire, and f(E) is the Fermi-distribution function. The current I flowing through the system in the small energy interval dE is the current injected into the left lead multiplied by the transmission coefficient T. This current ($I = \frac{e}{2\pi\hbar}T$) flowing around the Fermi energy E splits into two parts I_1 and I_2 at the junction J_1 and flows through the upper and lower arms of the loop respectively. Kirchoff's law of current conservation guarantees that $I = I_1 + I_2$. Since the upper and lower arm lengths are different, unequal current will flow through the two arms. We solve the problem quantum mechanically which is equivalent to solving a scattering problem using our earlier formalism of waveguide propagation in networks[4-7]. Analytical expressions for I, I_1, I_2 and T are too long to be reproduced here. We present our results graphically. We find that in the quantum regime there are two distinct possibilities. In certain range of Fermi energies the currents in the two arms i.e., I_1 and I_2 are individually less than I and they flow in the same direction as I which is in the direction of the applied field. However, in other range of Fermi energies it so happens that the current in one of the arms is larger than I (magnification property) and to conserve the total current at the junctions, the current in the other arm must flow opposite to the direction of I, i.e., opposite to the direction of the applied field. This negative steady state current continues to flow in the loop as a circulating current. The magnitude of this circulating current is taken to be the same as that of the negative current flowing in one of the arms. The direction of circulating current can be inferred as follows. Consider a case ($\mu_1 > \mu_2$) when the net current flow is in the right direction. If, for this case, the negative current flows in the lower (or upper) arm, then the positive (or negative) circulating current flows, clockwise (or anti-clockwise). Such a negative current is not possible classically.

With this definition of the circulating current (or persistent currents) we have plotted the circulating current (solid curve) versus dimensionless Fermi wave-vector in fig. 2. It is non-zero in certain range of Fermi wave-vector intervals. We have set $\hbar = 2m$=1 and so $k = \sqrt{E}$. We have chosen $(l_1 + l_2)/l_3$=5.0/3.0. The dimension-less total current through the system is the transmission coefficient and it is shown by the dotted line. The figure shows that the persistent current appears near the resonant states of the system around which the transmission goes to zero.

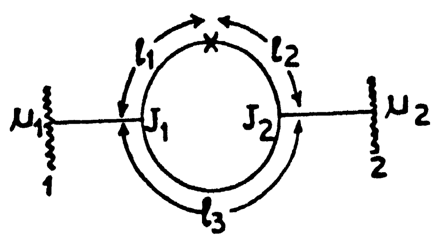

Fig. 1 metal loop connected to two electron reservoirs and there is a delta function impurity at the site X in the upper arm.

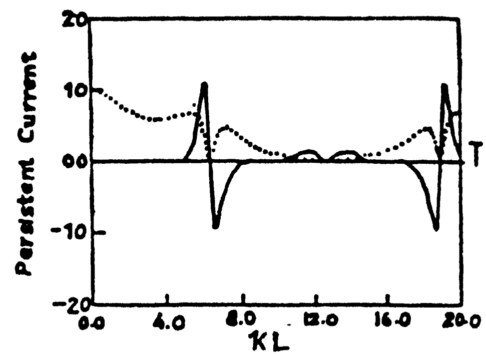

Fig. 2 Plot of persistent current vs dimensionless wave vector kL (solid curve), and transmission coefficient T vs kL (dashed curve) with $(l_1 + l_2)/l_2 = 5/3$.

Next we proceed to explore the effect of impurities on this circulating current. For this we have taken the strength of the delta function potential V_0 at the site X to be nonzero. The plot of circulating current versus (dashed curve) kL is shown in fig 3. Again we have chosen $(l_1 + l_2)/l_3$=5/3 but V_0L=1. The solid curve gives the circulating current when V_0L=0. The figure shows that the circulating current at the first peak has increased in magnitude and also shifted in position. The shift in the position is due to the fact that the impurity results in a change in the boundary conditions which shifts the resonances of the system, and we have already seen in fig. 1 that the circulating current appears around the resonances. However, the increase in magnitude of the circulating current inspite of the fact that the impurity enhances scattering is very counterintuitive. We can give a qualitative explanation based on the symmetry of the system. Consider a case when the impurity strength is zero and the length of the two arms of the loop are equal. Then due to the symmetry equal current will flow through the two arms i.e., $I_1 = I_2 = I/2$. Hence there is no way that the current in one arm can exceed I making the current in the other arm negative. So circulating current cannot occur in the loop. Now if we make the impurity strength non-zero then the impurity, not only introduces extra scattering, but also breaks the symmetry of the system. As a result I_1 need not be equal to I_2 and there is no principle restricting the individual value of these currents without violating the current conservation at the junctions. Hence the current in one arm can exceed the total current thus making the current in the other arm negative. This is in contrast to the fact that impurity always decreases the circulating currents in a closed ring in the presence of a magnetic field[1].

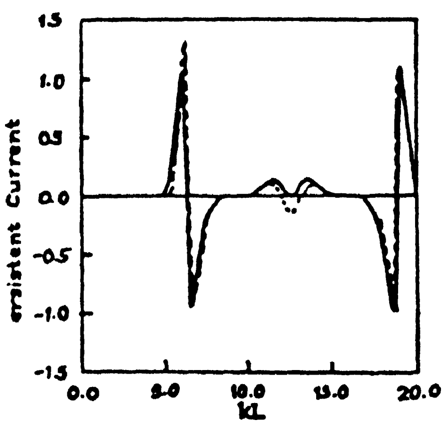

Fig. 3 Plot of persistent current vs kL for VL=0 (solid line) and VL=1 (dotted line) for the case when l_1/L = .3125, l_2/L = .3125 and l_3/L=.375.

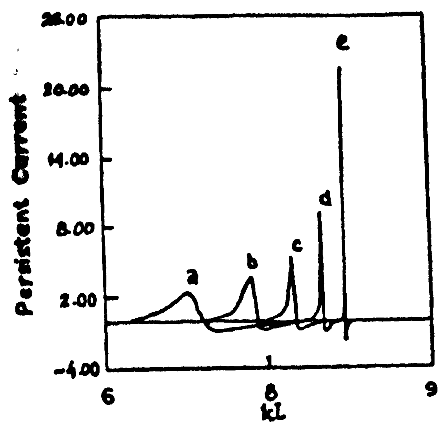

Fig. 4 Plot of persistent current vs kL for various values of VL in the first energy range. The curves a, b, c, d and e are for VL=5, 10, 15, 20 and 25 respectively. For all the curves $l_1/L = l_2/L$ =.3125 and l_3/L=.375

In fact there is no upper bound to the magnitude of the circulating current. This can be noticed by increasing the strength of the delta function potential. The circulating current in the first Fermi wave-vector range exhibits exotic features. In fig. 4 we have shown line shape of the circulating current in this energy range at different values of V_0, which however keeps changing as V_0 is changed. The curves a, b, c, d and e are for V_0L=5, 10, 15, 20 and 25, respectively. The peak value in the positive direction keeps increasing with the strength of the impurity potential whereas the peak value in the negative direction decreases slightly for the first four graphs and then increases a little for the last graph. The peak value in the positive direction actually has a divergence at V_0L=29 and

kL=8.37701785204. Beyond this point however the peak value drastically decreases as V_0 is increased further and finally the circulating current goes to zero. This is because asymptotically the system approaches a situation when the resistance of the upper arm becomes infinite and all the current flows through the lower arm, making circulating currents physically impossible. From fig.(4) one can conclude that impurities help in enhancing the circulating currents in some Fermi energy intervals and suppressing in other Fermi energy intervals, thus playing a dual role.

In conclusion we have shown theoretically that circulating currents can arise in the absence of a magnetic field in an open metallic loop connected to two electron reservoirs in the presence of a transport current. This is a quantum effect. These currents are very sensitive to the presence of impurities (to their strength and position). Since the magnetic moment of the loop is proportional to the line integral of the current along the entire circumference of the loop, due to the current magnification effect, we expect that one should observe enhanced magnetic response around particular Fermi energy intervals (around which transmission or two port conductance exhibits a minima).

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